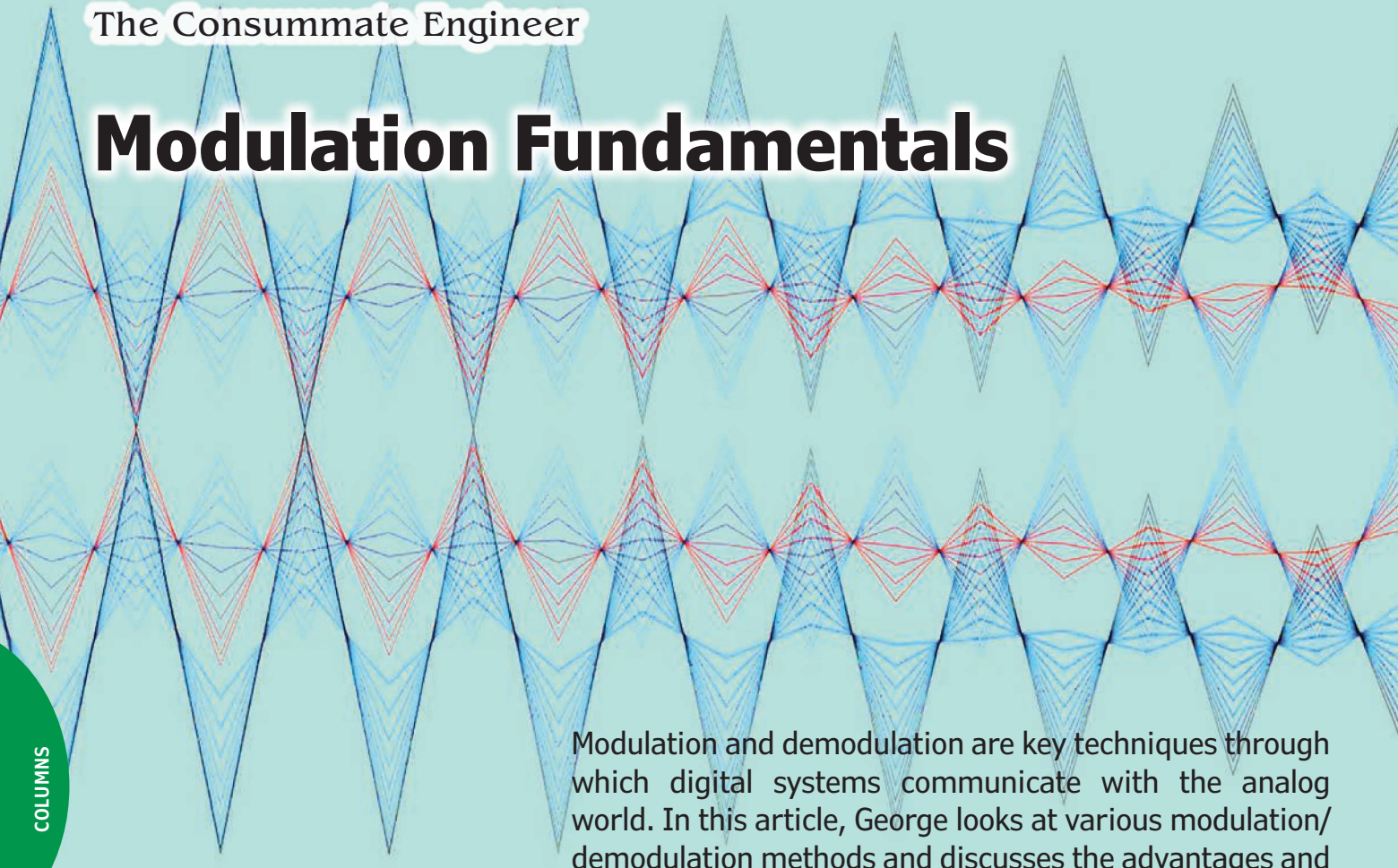
The Consummate Engineer

Modulation Fundamentals



COLUMNS

Modulation and demodulation are key techniques through which digital systems communicate with the analog world. In this article, George looks at various modulation/demodulation methods and discusses the advantages and disadvantages of each.

By
George Novacek

Many systems must communicate with the outside world. Often their information-bearing signal can be carried by wires, but this may not always be practical or even possible. Fortunately, the information-bearing signal can be altered—modulated—into another signal that is suitable for communication via radio, fiber optics, long cable and so forth. We call the original information the baseband and the modulated signal the carrier. Demodulation is a reverse process for retrieval of the baseband from the carrier.

In telephony, for example, every voice channel modulates a sub-carrier. The sub-carriers are combined to modulate higher frequency carriers and those once again may modulate an even higher carrier that may be transmitted over fiber optics or microwave links. Consequently, much information—voice and data—can be carried by a single transmission medium.

The oldest modulation technique is the amplitude modulation (AM). It is simple to implement and simple to demodulate. **Figure 1** shows an idealized frequency spectrum of an AM carrier. In North America, the highest AM radio program frequency is 5 kHz and should the carrier frequency be 1 MHz, the required bandwidth will be 995 kHz to 1005 kHz—10-kHz in total. Therefore, broadcast AM station carriers are spaced by 10-kHz to avoid interference within the AM radio operating band of 525 kHz to 1,705 kHz. The latest AM broadcast modulation can carry additional information such as stereo, but AM is rather inefficient in terms of its power and bandwidth requirements. It is also subject to noise and interference.

The interference could be reduced by increasing the transmitting power, but there are practical as well as regulatory limits. The power inefficiency is caused by the carrier, which consumes most of the power and contains no information. And the bandwidth—because it contains two mirror basebands—requires double the maximum modulation frequency. Several methods have been implemented to reduce these inefficiencies.

The first method is the reduction of the carrier amplitude—reducing it down to, in some systems, its full suppression. Because the carrier is needed for demodulation, it can be restored or regenerated by the receiver. The second method involves the sidebands. Because both sidebands carry identical information, one of them can also be suppressed, cutting the bandwidth by half. These modulation techniques are called: reduced or suppressed carrier with double sidebands (DSB) and a single sideband with suppressed carrier (SSB). Vestigial sideband modulation (VSB) is similar to SSB but requires greater bandwidth. It is used primarily in TV transmission. The on-off keying (OOK) is popular for simple data transmission, in key fobs and remote control.

OOK MODULATION

OOK modulation results when the baseband is a rectangular wave, such as digital data. In many applications the OOK modulation index is 100%—such as when the carrier is fully on or off. In the days of Morse code communications, the continuous wave (CW) transmission mode was a typical OOK modulation. Some applications—namely the WWVB transmission for clock synchronization—use 86% modulation index to prevent receivers from losing synchronization during transmission of logical 0s.

Three characteristics define the AM modulation: the carrier frequency, the bandwidth and the modulation index. **Figure 2a** shows 100% and **Figure 2b** 50% modulation index (depth). Amplitude modulators come in many different configurations and are quite simple to build. One of the early implementations was the bridge modulator shown in **Figure 3**. **Figure 4** shows the WWVB, 86% depth modulator I built for my 60-kHz carrier transmitter in the WWVB repeater. This was covered in my article "WWVB Clock Revisited" (*Circuit Cellar* 288, July 2014). In this circuit the MOSFET Q1 operates in its resistive region to modulate the gain of the carrier amplifier U1A.

Demodulation of the broadcast AM signal is commonly performed by envelope detectors, which can be nothing more than a simple rectifier diode followed by an RC network. The time constant of this network must be much larger than the carrier frequency period and much smaller than the shortest baseband period (the highest baseband frequency). This is generally not a problem in practical systems.

Demodulation of DSB and SSB are more complicated because the carrier needs to be restored. A suppressed carrier can be easily recovered by amplification. The fully

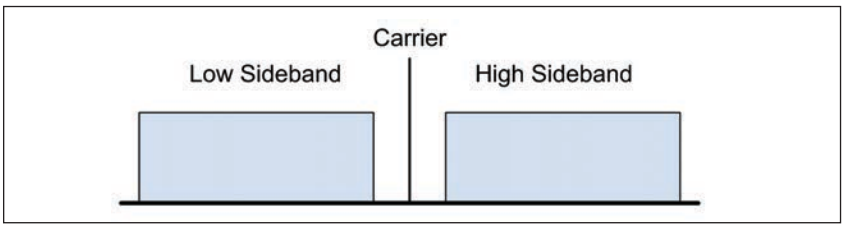


FIGURE 1
Frequency spectrum of an AM modulated signal (not to scale)

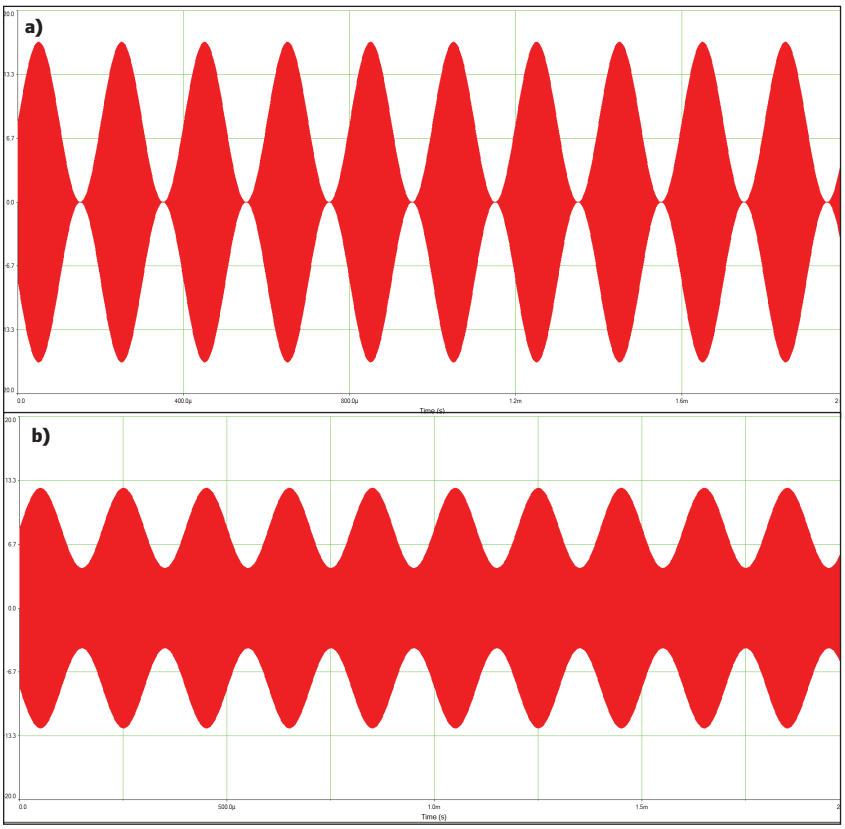


FIGURE 2
In the top graph (a) a 100% modulation index is shown. The bottom one (b) shows a 50% modulation index.

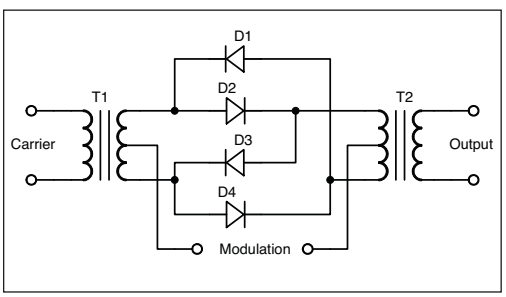


FIGURE 3
Bridge AM modulator

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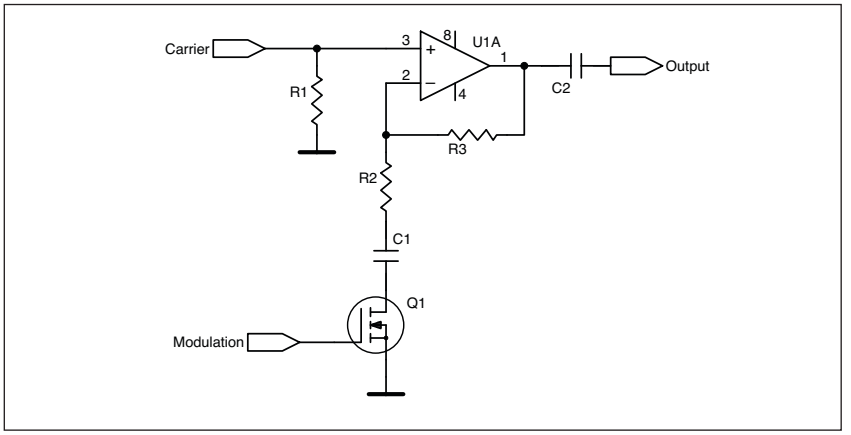

FIGURE 4
Simplified diagram of the WWVB modulator

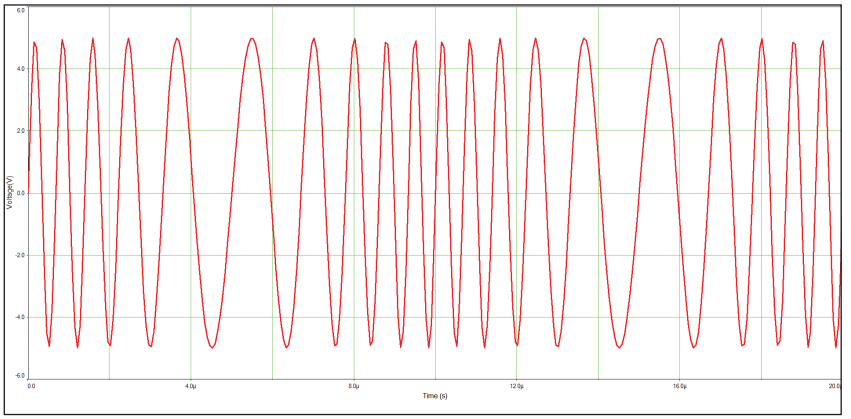

FIGURE 5
Frequency modulated carrier

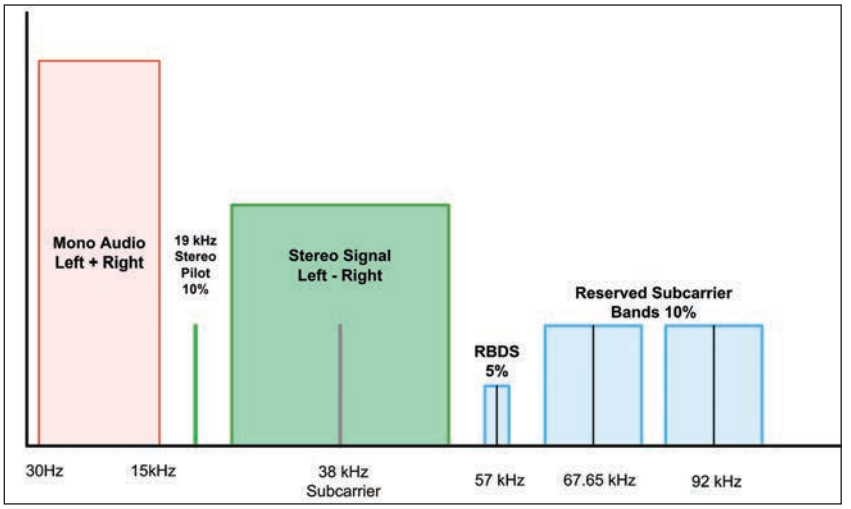

FIGURE 6
Multiple modulation of an FM broadcast carrier

suppressed carrier is regenerated by a stable local oscillator as we can see in ham radio receivers. Another method for modulating a carrier is by changing its frequency or phase. Such modulation techniques can be seen in four basic configurations: Frequency modulation (FM) also used for commercial broadcast, phase modulation (PM), frequency shift keying (FSK) and phase shift keying (PSK). **Figure 5** shows the FM carrier in frequency domain.

FM AND PM MODULATION

Similar to the AM, the main characteristics of the FM and the PM modulation are the carrier frequency, the required bandwidth and the modulation index. The modulation index is the frequency or phase deviation of the carrier in response to the modulation signal. PM is similar to the FM except that instead of changing the carrier frequency, which remains constant, only its phase is modulated. In the time domain analysis, both FM and PM look the same, just the deviation magnitudes are different. The FSK and the PSK modulations are used for transmission of logical data, because the frequency and the phase change in discrete steps.

FM carriers often contain multiple sub-carriers for additional information. **Figure 6** shows the baseband spectrum of a typical FM broadcast station. The stereo information is modulated on a 38-kHz subcarrier generated from the 19-kHz pilot. Several other information bands, originally designed for quadraphonic music, can be transmitted on additional subcarriers.

There are many ways to perform FM, PM, FSK and PSK modulation of a carrier signal. One of the original approaches was to utilize varactor diodes (diodes whose capacitance can be varied by voltage) in the carrier generator. Nowadays many modulators use a phase locked loop (PLL), which can include a reference crystal oscillator to guarantee high stability of the carrier (**Figure 7**).

PLLs are available as integrated circuits and only a few external components need to be added. A PLL is in fact an electronic feedback servo system. A stable crystal-generated carrier frequency is fed into the phase detector which compares the frequency of the voltage controlled oscillator (VCO) with the reference. Because of the (optional) divider, the carrier frequency may be a multiple of the reference. The error signal from the phase detector to adjusts the VCO frequency is modulated by the baseband, causing the carrier frequency or phase to deviate accordingly.

Quadrature amplitude modulation (QAM) is a sophisticated modulation known by many

readers as the heart of the old "high-speed" 56k telephone modems. It is a combination of AM and PM. Given the limited bandwidth of the old analog telephone channels, QAM pushed its information carrying ability almost up to the theoretical limit.

ADVANTAGES FOR EACH

Each modulation technique has its advantages, disadvantages and applications. AM has been used in radio broadcasting since the birth of radio. Its modulation and demodulation are easy to implement and the receivers are rather inexpensive to build. DSB is used in instrumentation systems utilizing carrier amplifiers and modulating sensors, while SSB finds its use in certain radio communications, many by ham amateurs. Its derivative VSB modulates television signals. FM provides much better audio quality than the AM and, therefore, is used in broadcasting (radio and television audio). Its narrow bandwidth version and PM rule point-to-point mobile communications. FSK and PSK are employed for digital communications, while the analog QAM carries the chrominance (color) information in television broadcasting and the OOK is commonly found in remote control systems, key fobs and some digital data transmitters.

For completeness we should mention two special modulations: frequency hopping and spread spectrum modulation. These modulations do not carry information per se. The former is intended to increase communications security while the latter improves electromagnetic compatibility (EMC) of electronic systems.

Over the years numerous circuits have been developed for demodulation of FM, PM and other modulations. Older demodulators used the slope of LC resonant circuits, then came ratio detectors, PLLs, quadrature demodulators and others. Nowadays PLLs (**Figure 8**) are still used for both FM and PM demodulation, but this is quickly changing. Our present-day technology facilitates the development of digital radio, which relies on digitization of the carrier frequency. This makes possible digital signal processing and may be followed by conversion of the digital data back to analog to recreate the baseband. Whether data or voice communications are involved makes little difference. Digitization of 10 GHz carrier is already a reality and once digitized, the skies are the limits for further processing.

I intentionally omitted the pulse width modulation (PWM). This is a technique for conversion of digital signals to analog power and not fitting the current topic.

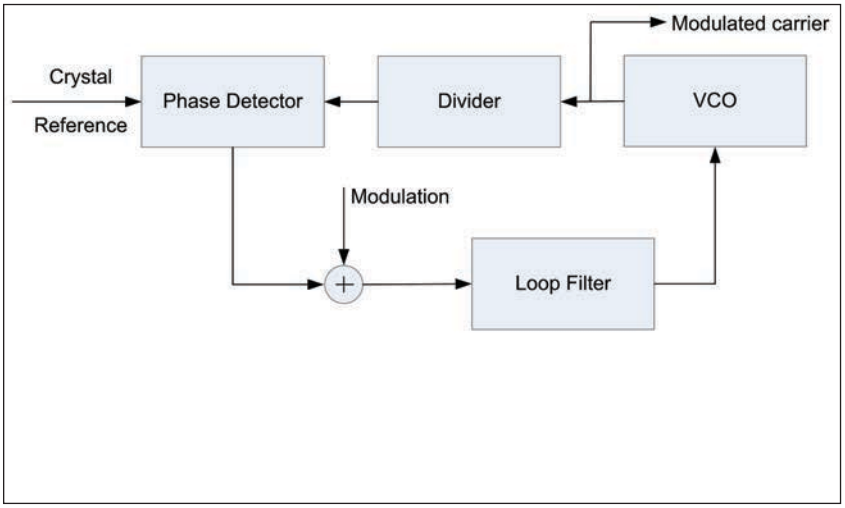

FIGURE 7
Principle of phase and/or frequency modulation by PLL

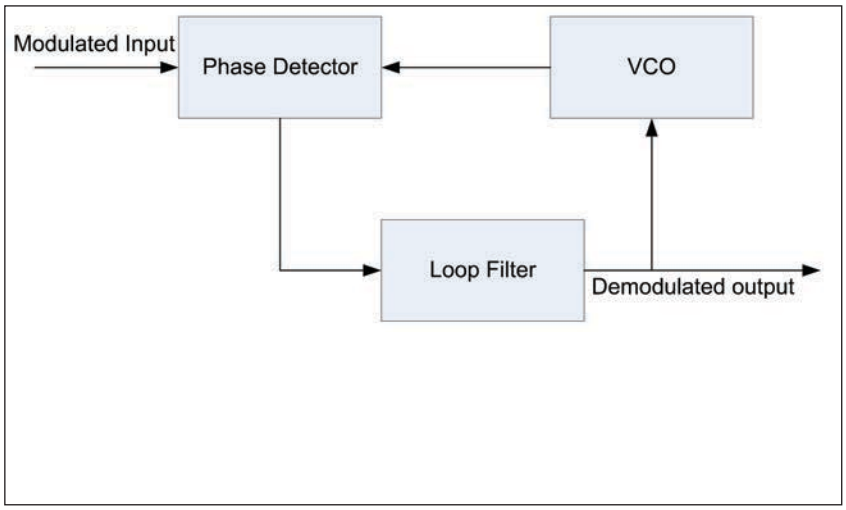

FIGURE 8
PLL demodulator

ABOUT THE AUTHOR

George Novacek is a retired president of an aerospace company. He is a professional engineer with degrees in Automation and Cybernetics. George's dissertation project was a design of a portable ECG (electrocardiograph) with wireless interface. He's been contributing articles to *Circuit Cellar* since 1999. Contact him at gjnovacek@nexicom.net with "Circuit Cellar"in the subject line.